Soil Biology & Biochemistry 43 (2011) 1812–1836

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

Review

Biochar effects on soil biota – A review

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ARTICLE INFO

Article history:
Received 14 December 2010
Received in revised form
6 April 2011
Accepted 28 April 2011
Available online 18 May 2011

Keywords:
Activated carbon
Biochar
Black carbon
Charcoal
Fauna
Microorganisms
Roots

ABSTRACT

Soil amendment with biochar is evaluated globally as a means to improve soil fertility and to mitigate climate change. However, the effects of biochar on soil biota have received much less attention than its effects on soil chemical properties. A review of the literature reveals a significant number of early studies on biochar-type materials as soil amendments either for managing pathogens, as inoculant carriers or for manipulative experiments to sorb signaling compounds or toxins. However, no studies exist in the soil biology literature that recognize the observed large variations of biochar physico-chemical properties. This shortcoming has hampered insight into mechanisms by which biochar influences soil microorganisms, fauna and plant roots. Additional factors limiting meaningful interpretation of many datasets are the clearly demonstrated sorption properties that interfere with standard extraction procedures for soil microbial biomass or enzyme assays, and the confounding effects of varying amounts of minerals. In most studies, microbial biomass has been found to increase as a result of biochar additions, with significant changes in microbial community composition and enzyme activities that may explain biogeochemical effects of biochar on element cycles, plant pathogens, and crop growth. Yet, very little is known about the mechanisms through which biochar affects microbial abundance and community composition. The effects of biochar on soil fauna are even less understood than its effects on microorganisms, apart from several notable studies on earthworms. It is clear, however, that sorption phenomena, pH and physical properties of biochars such as pore structure, surface area and mineral matter play important roles in determining how different biochars affect soil biota. Observations on microbial dynamics lead to the conclusion of a possible improved resource use due to co-location of various resources in and around biochars. Sorption and thereby inactivation of growth-inhibiting substances likely plays a role for increased abundance of soil biota. No evidence exists so far for direct negative effects of biochars on plant roots. Occasionally observed decreases in abundance of mycorrhizal fungi are likely caused by concomitant increases in nutrient availability, reducing the need for symbionts. In the short term, the release of a variety of organic molecules from fresh biochar may in some cases be responsible for increases or decreases in abundance and activity of soil biota. A road map for future biochar research must include a systematic appreciation of different biochar-types and basic manipulative experiments that unambiguously identify the interactions between biochar and soil biota.

1. Introduction

Biochar is the product of thermal degradation of organic materials in the absence of air (pyrolysis), and is distinguished from charcoal by its use as a soil amendment (Lehmann and Joseph, 2009). Biochar has been described as a possible means to improve soil fertility as well as other ecosystem services and sequester carbon (C) to mitigate climate change (Lehmann et al., 2006; Lehmann, 2007a; Laird, 2008; Sohi et al., 2010). The observed effects on soil fertility have been explained mainly by a pH increase in acid soils (Van Zwieten et al., 2010a) or improved nutrient retention through cation adsorption (Liang et al., 2006). However, biochar has also been shown to change soil biological community composition and abundance (Pietikäinen et al., 2000; Yin et al., 2000; Kim et al., 2007; O'Neill et al., 2009; Liang et al., 2010;

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0038-0717/$ – see front matter
doi:10.1016/j.soilbio.2011.04.022

Grossman et al., 2010; Jin, 2010). Such changes may well have effects on nutrient cycles (Steiner et al., 2008b) or soil structure (Rillig and Mummey, 2006) and, thereby, indirectly affect plant growth (Warnock et al., 2007). Rhizosphere bacteria and fungi may also promote plant growth directly (Schwartz et al., 2006; Compant et al., 2010). The possible connections between biochar properties and the soil biota, and their implications for soil processes have not yet been systematically described.

The effectiveness of using biochar as an approach to mitigate climate change rests on its relative recalcitrance against microbial decay and thus on its slower return of terrestrial organic C as carbon dioxide (CO_2) to the atmosphere (Lehmann, 2007b). Both the composition of the decomposer community as well as metabolic processes of a variety of soil organismal groups may be important in determining to what extent biochar is stable in soils, as is known for wood decay (Fukami et al., 2010). Changes in microbial community composition or activity induced by biochar may not only affect nutrient cycles and plant growth, but also the cycling of soil organic matter (Wardle et al., 2008; Kuzyakov et al., 2009; Liang et al., 2010). In addition, biochar may change emissions of other greenhouse gases from soil such as nitrous oxide (N_2O) or methane (CH_4) (Rondon et al., 2005; Yanai et al., 2007; Spokas and Reicosky, 2009; Clough et al., 2010; Singh et al., 2010; Zhang et al., 2010; Taghizadeh-Toosi et al., 2011). Such changes may either reduce or accelerate climate forcing. The driving processes are still poorly identified (Van Zwieten et al., 2009). A more rapid mineralization of indigenous soil C or greater emission of other greenhouse gases as a result of biochar additions may counteract the benefits of reduced emissions elsewhere in the life cycle of a biochar system. A systematic examination of the ways in which different microbial and faunal populations may play a role in these biogeochemical processes is still lacking.

Biochar may pose a direct risk for soil fauna and flora, but could also enhance soil health. Biochar addition may affect the soil biological community composition as demonstrated for the biochar-rich Terra preta soils in the Amazon (Yin et al., 2000; Kim et al., 2007; O'Neill et al., 2009; Grossman et al., 2010), and has been shown to increase soil microbial biomass (Liang et al., 2010; O'Neill et al., 2009; Jin, 2010). Whether the abundance of microorganisms increases or not, as discussed for mycorrhizal fungi (Warnock et al., 2007), is likely connected to the intrinsic properties of both biochar and the soil. Biochar properties vary widely and profoundly; not only in their nutrient contents and pH (Lehmann, 2007a), but also in their organo-chemical (Czimczik et al., 2002; Nguyen et al., 2010) and physical properties (Downie et al., 2009). The role of biochar in soil biological processes therefore represents a frontier in soil science research, with many unexplained phenomena awaiting exploration. Recent advances in our understanding of biochar warrant an evaluation of the relationship between its properties and its impact on the soil biota.

In this paper, we critically examine the state of knowledge on soil populations of archaeans, bacteria, fungi, and fauna as well as plant root behavior as a result of biochar additions to soil. We develop concepts for a process-level understanding of the connection between biochar properties and biological responses, discuss the ramifications of such changes for biogeochemical processes in soil, and develop a road map for future research.

2. Modification of the soil habitat by biochar

The material properties of biochar are very different from those of uncharred organic matter in soil (Schmidt and Noack, 2000), and are known to change over time due to weathering processes, interactions with soil mineral and organic matter and oxidation by microorganisms in soil (Lehmann et al., 2005; Cheng et al., 2008; Cheng and Lehmann, 2009; Nguyen et al., 2010). However, the relationships between biochar chemical and physical properties and their effects on soil biota and potential concomitant effects on soil processes are poorly understood. This section gives a brief overview of the unique properties of biochars compared to other compounds in soil as a background to the following sections that discuss the effects of biochar on soil biota.

2.1. Basic properties: organic and inorganic composition

Biochar composition can be crudely divided into relatively recalcitrant C, labile or leachable C and ash. The greatest chemical difference between biochar and other organic matter is the much larger proportion of aromatic C and, specifically, the occurrence of fused aromatic C structures (Table 1), in contrast to other aromatic structures of soil organic matter such as lignin (Schmidt and Noack, 2000). This fused aromatic structure of biochars in itself can have varying forms, including amorphous C, which is dominant at lower pyrolysis temperatures, and turbostratic C, which forms at higher temperatures (Keiluweit et al., 2010; Nguyen et al., 2010). It is clear that the nature of these C structures is the chief reason for the high

Table 1
Physical and chemical properties of contrasting biochars relevant to biological processes in soil (Nguyen and Lehmann, 2009; Nguyen et al., 2010; Enders, Hanley and Lehmann, unpubl. data; Hockaday, unpubl. data).

Feedstock	Temperature (°C)	pH (KCl)	pH (H_2O)	CEC[a] (mmolc kg^{-1})	CEC[a] (molc m^{-2})	C (%)	C/N ratio	Total P (mg kg^{-1})	Ash[b] (%)	Volatiles[b] (%)	Fixed C[b] (%)	H/C ratio[c]	O/C ratio[c]	Aromatic C[d] (% of total)	Aromatic clusters	SSA[e] (m^2 g^{-1})
Oak wood	60	3.16	3.73	182.1	ND[f]	47.1	444	5	0.3	88.6	11.1	1.48	0.72	ND	ND	ND
	350	5.18	4.80	294.2	0.65	74.9	455	12	1.1	60.8	38.1	0.55	0.20	82.8	18	450
	600	7.90	6.38	75.7	0.12	87.5	489	29	1.3	27.5	71.2	0.33	0.07	86.6	37	642
Corn stover	60	6.33	6.70	269.4	ND	42.6	83	526	8.8	85.2	6.0	1.56	0.74	2.0	6	ND
	350	9.39	9.39	419.3	1.43	60.4	51	1889	11.4	48.8	39.8	0.75	0.29	76.9	19	293
	600	9.42	9.42	252.1	0.48	70.6	66	2114	16.7	23.5	59.8	0.39	0.10	88.2	40	527
Poultry litter	60	7.53	7.53	363.0	ND	24.6	13	16,685	36.4	60.5	3.1	1.51	1.03	ND	ND	ND
	350	9.65	9.65	121.3	2.58	29.3	15	21,256	51.2	47.2	1.6	0.57	0.41	ND	ND	47
	600	10.33	10.33	58.7	0.63	23.6	25	23,596	55.8	44.1	0.1	0.18	0.62	ND	ND	94

[a] Cation exchange capacity, determined at pH 7 using buffered ammonium acetate (Nguyen and Lehmann, 2009).
[b] Mass % w/w analyzed using ASTM D1762-84.
[c] Molar ratios.
[d] In rings, determined by direct polarization ^{13}C nuclear magnetic resonance spectroscopy.
[e] Specific surface area, CO_2 as sorbent (courtesy A. Zimmerman).
[f] Not determined.